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vs a composite dimensionless graph of
)ints directly downstream or not inline with the

NCLUSIONS

following trends are found in profiles measured

low within the shorter vegetation appears to be

:urs at a point near the top, but lower than the

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Climate Change Impact on Hydrology and Lake Thermal Structure

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ABSTRACT

The impact of climate warming on basin hydrology and lake responses is examined for the Great Lakes region and also considered for other climatic areas. Based on case studies which considered observations, steady-state and transient GCM scenarios, transposition climates, and responses of lakes in a range of climatic zones, it is demonstrated that climate warming can have significant impact on basin hydrological components and can affect thermal and stratification characteristics of lakes.

INTRODUCTION

General circulation models (GCMs) have indicated that under 2×CO_2 atmospheric concentration scenarios, the natural greenhouse effect of the atmosphere will be enhanced, potentially leading to higher global atmospheric temperatures. Climate warming has the potential to affect the physical, chemical and biological characteristics of a region including aquatic systems. Investigations are ongoing to assess probable impacts of climate warming on various sectors of the environment and economy and to assess potential adaptive/mitigative strategies. This paper provides a discussion of potential basin and lake responses under several climate change scenarios. We focus on the Great Lakes basin, which is a dominant feature on the North American Continent with the largest continuous volume of freshwater on Earth, and consider sensitivities in other climatic regimes.

CLIMATE CHANGE AND REGIONAL SCENARIOS

Potential changes in large lake climate conditions are based on predictions from GCMs for 2×CO_2 atmospheric conditions from: the Goddard Institute for Space Studies (GISS), Geophysical Fluid Dynamics Laboratory (GFDL), Oregon State University (OSU) and Canada Climate Centre [CCCII (second generation model)]. The basic premise in many investigations is that regional models can link to GCM outputs to assess climate change changes. GCM steady-state and transient simulations are formed into monthly and seasonal climate statistics at grid-point locations for air temperature, precipitation, wind speed, humidity, and clouds. In general, GCM models do not provide meaningful simulations of sub-synoptic scale features; this is a significant limita-

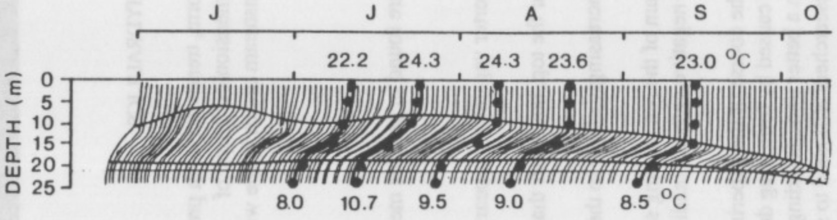

Fig. 1. Simulated & Observed 1983 Lake Erie Daily Temperature Profiles.

tion for formulation of regional climate change scenarios, often forcing the use of inappropriately large spatial and temporal scales. Also, applying ratios, averages, or interpolations of GCM outputs to subgrid scales does not completely address spatial or temporal variability changes. Essentially, such an application maintains the variability and seasonal patterns inherent in the base climate. Never-the-less, such case studies can illustrate potential responses of large lake systems to climate changes.

Observed Lake Response to a Warm Climate

Schertzer and Sawchuk (1990) examined the thermal structure of Lake Erie for an anomalously warm year (1983) to infer the potential response for thermocline characteristics and anoxia occurrence under warm conditions. They found that 1983 was characterized by large reductions in surface heat losses in winter and above average surface heat flux gains in summer. Observations indicated higher surface water temperatures, significant reductions in the extent and duration of ice cover, and an earlier start to thermal stratification. The thermocline formed higher in the water column (Fig. 1), and stratification lasted longer than in other years, contributing to slight hypolimnetic anoxia in the central basin in the latter half of September (Schertzer and Lam 1991).

Simulated Lake Ontario Response to a Warm GCM Climate

Boyce et al. (1993) examined the thermal response of Lake Ontario based on a CCCII GCM climate change scenario and application of the one-dimensional Dynamic Reservoir Simulation Model (DYRESM). Croley (1993) looked at thermal responses of all Great Lakes based also on a CCCII GCM climate change scenario and application of the Great Lakes Environmental Research Laboratory (GLERL) large lake thermodynamics and heat storage model. Both investigations found that in the simulated climate change, Lake Ontario no longer experiences spring and fall convective overturn (i.e. > 4°C water at the surface); see Fig. 2. The stratified period is two months longer and maximum surface water temperatures are 4°C higher than the base case climate. Minimum summertime temperature throughout the lake is computed to be 6°C. Further investigation indicated that the thermal structure (i.e. epilimnion water temperature, thermocline gradients, mixed layer depth and length of stratification period) was sensitive to variation in seasonal and annual air temperature and wind speed changes.

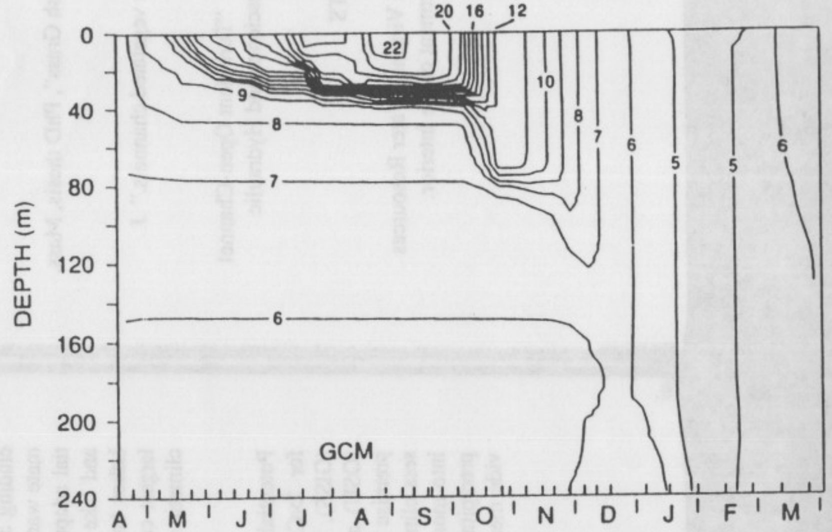

Fig. 2. Simulated 2×CO_2 Lake Ontario Temperatures (CCCII & DYRESM).

Simulated Hydrology Response to a Warm GCM Climate

GLERL investigated mean responses in hydrological variables for the Great Lakes basin, summarized in Table 1, by using steady-state 2×CO_2 atmospheric scenarios from three GCMs (Croley 1990). Monthly adjustments of "present" to 2×CO_2 steady-state conditions from GISS, GFDL, and OSU were applied to daily historical data sets to

Table 1. Average Annual Steady-State Great Lakes Basin Hydrology Summary.

Scenario (1)	Over-land Precip. (2)	Evapo-transpir. (3)	Basin Runoff (4)	Over-lake Precip. (5)	Over-lake Evap. (6)	Net Basin Supply (7)
Current	13855 m^3s^{-1}	7814 m^3s^{-1}	6206 m^3s^{-1}	6554 m^3s^{-1}	4958 m^3s^{-1}	7803 m^3s^{-1}
General Circulation Model Simulations						
GISS	2 %	21 %	-24 %	4 %	27 %	-37 %
GFDL	1 %	19 %	-23 %	0 %	44 %	-51 %
OSU	6 %	19 %	-11 %	6 %	26 %	-23 %
CCC	-2 %	22 %	-32 %	0 %	32 %	-46 %
Transposed Climate Simulations						
6°S×10°W	+6%	+31%	-25%	+3%	+49%	-48%
6°S×0°W	+24%	+43%	-1%	+25%	+33%	-1%
10°S×11°W	+17%	+48%	-21%	+13%	+75%	-54%
10°S×5°W	+45%	+78%	+2%	+45%	+69%	-5%

estimate 33-year sequences of atmospheric conditions associated with the 2×CO_2 scenarios. The 2×CO_2 scenarios were applied in hydrology impact model simulations and differences between the 2×CO_2 scenario and the base case scenario were interpreted as resulting from the changed climate. Table 1 indicates that for the Great Lakes basin, the three scenarios changed precipitation little but snow-melt and runoff were greatly decreased, evapotranspiration and lake evaporation were greatly increased, and net basin supplies (NBS) to the lakes and lake levels were decreased. The GFDL GCM scenario was the most extreme, with evaporation 44% higher than the base case and NBS less than 50% of the base case. A CCCII GCM steady-state climate scenario over the period 1948-88 (Croley 1993) proved similar to the GFDL-based scenario in that net basin supplies were reduced to almost 50% of the base case. However, the CCC-based scenario reduced runoff more and evaporation less than the GFDL-based scenario (Table 1). A GISS GCM transient climate scenario for selected hydrological components for individual lake basins over the period 1981-2060 (Table 2) shows dramatic changes in annual basin evapotranspiration, annual lake evaporation, annual NBS, and annual net outflow, and an overall reduction in lake levels.

Simulated Great Lakes Response to Transposed Climates

The impact of climatic variability is an important consideration requiring a long-term data base capable of assessing variability and sensitivity of fluctuations. Croley et.al. (1996) transposed current climatic conditions from the south and west of the Great Lakes to the Great Lakes region to develop climate scenarios assuming that future

Table 2. GISS Transient Climate Changes Impacts Summary.

Hydrological Variable	Units	Basin					
		Sup.	Mic.	Hur.	StC.	Eri.	Ont.
Basin Air Temperature	°C/dec	+0.5	+0.6	+0.6	+0.6	+0.6	+0.6
Annual Basin Precipitation	mm/dec	+29	+7	+2	-0	+3	+1
Annual Basin Evapotranspir.	mm/dec	+25	+14	+12	+15	+16	+16
Annual Basin Runoff	mm/dec	+4	-7	-9	-15	-15	-14
Snow Pack	mm/dec	-4	-1	-4	-1	-0.7	-2
Soil Moisture	mm/dec	+0.5	-0.8	-1	-0.4	-0.4	-0.6
Groundwater	mm/dec	+2	-1	-0.3	-0.4	-0.4	-0.3
Total Basin Moisture	mm/dec	-0.1	-4	-5	-2	-2	-4
Lake Air Temperature	°C/dec	+0.7	+0.6	+0.6	+0.6	+0.6	+0.6
Lake Humidity	mb/dec	+0.6	+0.5	+0.5	+0.7	+0.7	+0.6
Lake Cloud Cover	%/dec	+0.1	-0.2	-0.5	-0.4	-0.5	-0.5
Lake Wind Speed	m/s/dec	+0.0	+0.0	+0.0	+0.0	+0.0	-0.0
Surface Temperature	°C/dec	+0.7	+0.5	+0.6	+0.5	+0.6	+0.6
Annual Lake Evaporation	mm/dec	+18	+19	+22	+38	+40	+24
Annual Net Basin Supply	mm/dec	+17	-27	-41	-245	-75	-75
Annual Net Outflow	mm/dec	+20	-31	-31	-241	-70	-57
Lake Level	mm/dec	-13	-59	-59	-64	-66	-93

changes in the basin climate may approximate latitudinal and/or longitudinal climatic shifts. Table 1 illustrates results based on four transposed climate scenarios: 1) warm and dry (6°S×10°W), 2) warm and wet (6°S×0°W), 3) very warm and dry (10°S×11°W), and 4) very warm and wet (10°S×5°W). Scenarios 1 and 2 correspond roughly to the upper range of GCM predictions for temperature for the Great Lakes basin while Scenarios 3 and 4 went beyond the range of current GCM 2×CO_2 predictions in order to determine how the Great Lakes would respond to a major climatic shock.

All transposition scenarios produced significant increases in lake evaporation (Table 1). Many scenarios resulted in lower soil moisture and reduced runoff despite higher precipitation and total annual evapotranspiration increases in all scenarios. Higher temperatures significantly reduced total snowfall and in the four scenarios, the snow-melt season is shorter and less significant In a warmer climate, greater precipitation is required to maintain runoff at present levels. As a result of increased lake evaporation and decreased runoff a significantly greater precipitation is required to maintain NBS at current levels of the Great Lakes; all transposed climate scenarios indicate decreased NBS with much higher variability. Inter-annual variability in NBS exhibits an average increase of about 60% in warm scenarios 1 and 2, and about 90% in very warm scenarios 3 and 4, due primarily to increased variability in precipitation. Great Lakes water levels are lower and more variable under the transposed climates, which has significant implications for flows in the connecting channels. Under scenarios 1 and 3, Lake Superior would have negative water supplies for all or part of the time. Under scenario 3 Lake Superior would become a terminal lake. Most scenarios indicated greater variability of lake levels, both seasonal and inter-annual, than exist in the present regime.

POTENTIAL IMPACTS ON OTHER LAKES

Meyer et al. (1994) considered the thermal responses of hypothetical lakes (i.e. 100 km^2) for shallow, intermediate, and deep configurations. A GFDL 2×CO_2 climate change scenario was used and regional sensitivity analyses of lake stratification on air temperature change were performed for every 5 degrees of latitude. In subtropical regions shallow and intermediate lakes, stratification was slightly sensitive to changes in air temperature while significant sensitivity was found in deep lakes. In temperate and polar regions, sensitivity of lake stratification to changes in air temperature was important for all lake depths. Turn-over characteristics of subtropical and sub-polar lakes were significantly affected by warmer atmospheric temperatures as turnover began earlier than under current conditions and the well mixed layer duration was longer. Cooler atmospheric temperatures were found to delay the onset of lake turnover and reduce the period of well mixed conditions. This investigation suggested that the effect of changing climate is equivalent to the corresponding change in geographic location (approximately one latitude degree per one degree Celsius of air temperature). Lake responses to climate change were highly sensitive near transition latitudes ranging from 30° to 45° N/S and 65° to 80° N/S.

SUMMARY

Examples of several methodologies for assessment of potential responses of the Great Lakes to climatic change indicated that under various scenarios climate warming can be expected to impact on basin hydrology and lake thermal conditions. A warmer climate is expected to increase both basin evapotranspiration and evaporation from the lakes. Changes in precipitation could result in decreased soil moisture and runoff, and with air temperature changes especially reduce spring snow-melt runoff. A reduction in NBS is likely which will lower flows in connecting channels and lake levels. Warmer conditions with reduced wind mixing can affect thermal stratification characteristics of the Great Lakes which has implication for water quality conditions. Climate transposition experiments reinforced observational and steady-state climate studies, concluding that significantly warmer climate reduces the frequency of buoyancy-driven water column turnovers from a frequency of two times/year to once per year. Significant hydrodynamic and environmental impacts are anticipated with warmer conditions and especially with reduced turnover frequency. With respect to water quality considerations, turnovers are important for such processes as vertical mixing of nutrients and oxygenation of lake water. Examination of hypothetical lakes over a range of latitudinal climates demonstrated that there are latitudinal zones in which lakes of varying sizes may be particularly sensitive to climate changes.

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Recent advances in

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